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# PHYSICS-OF-FAILURE DESIGN ANALYSES AND CONDITION BASED MAINTENANCE APPLICATIONS TO IMPROVE THE RELIABILITY AND SUPPORTABILITY OF ARMY SYSTEMS

JULY 2007



U.S. ARMY MATERIEL SYSTEMS ANALYSIS ACTIVITY
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| 13. ABSTRACT (Maximum 200 words)<br>Army Physics of Failure (PoF) design analyses and condition based maintenance applications have and will continue to improve the reliability and supportability of multiple systems. The PoF examples will show how dynamic modeling, fatigue modeling, finite element analyses, vibrations analysis, and thermal modeling have addressed potential reliability shortfalls and provided better products for our Warfighters. Such PoF analyses are most beneficial when performed during the early design and low-level testing process. However applications to systems already in the hands of our soldiers can provide significant returns. The condition based maintenance portion will show emerging results from multiple operational and logistics parameters that are being collected from different types of vehicles. The data are being captured from the vehicle data bus, external accelerometers, a six degree of freedom motion pack, and GPS. The paper will explain how templates are being developed to provide soldiers and life-cycle management center staff an easy way to assess vehicle utilization, environment, and other key parameters and conditions. The condition based maintenance results have great potential to improve Army vehicle fleet management capabilities, improve reliability, and address specific component failures. Both the PoF reliability improvement and condition based maintenance efforts are greatly helping our Warfighters. | | | |
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# PHYSICS-OF-FAILURE DESIGN ANALYSES AND CONDITION BASED MAINTENANCE APPLICATIONS TO IMPROVE THE RELIABILITY AND SUPPORTABILITY OF ARMY SYSTEMS

## 1. INTRODUCTION

Reliability of Army systems is a critical element in providing effective equipment in a cost effective manner to the Warfighter. Reliability directly impacts the vast majority of the life cycle costs of an Army system. With the increasing complexity of military systems, techniques to improve reliability need to be applied early in the development of new equipment. Physics of Failure (PoF) and Condition Based Maintenance (CBM) are two techniques that can have far-reaching effects on the reliability of Army systems.

## 2. PHYSICS OF FAILURE

Physics of Failure is a science-based approach to reliability that uses modeling and simulation to design-in reliability. This approach models the root causes of failures such as fatigue, fracture, wear, and corrosion. Computer-Aided Design (CAD) tools have been developed to address various loads, stresses, failure mechanisms and sites. The two main focus areas are in electronic and mechanical systems analyses. PoF uses knowledge of basic failure processes to prevent failures through robust design and manufacturing practices, and aims to

- Design-in reliability up front
- Eliminate failures prior to testing
- Increase fielded reliability
- Promote rapid, cost effective deployment of Health and Usage Monitoring Systems (HUMS)
- Improve diagnostic and prognostic techniques and processes
- Decrease operation and support costs

**2.1. Physics of Failure of Electronic Systems.** Electronic systems are analyzed through thermal analysis, vibrations analysis, fatigue analysis, and through a number of different failure mechanism analyses designed to eliminate potential failure modes. The Army Materiel Systems Analysis Activity (AMSAA) has many examples of where PoF was used to analyze the root cause of a failure. One such example examined the incorporation of Ball Grid Array technology for electronic packages on an Army Missile. AMSAA conducted a PoF analysis on the Army Missile to quantify the life consumed over the missile's storage, transportation, and launch cycles. There was concern with the fatigue of solder balls due to thermal and vibrations cycling. If solder balls were susceptible to fatigue, the missile could have an open circuit created during its storage, transportation or launch cycle. This would cause overall system failure. The results of the analysis showed that the new soldering technology did not cause any of the electronic packages which were used in the missile to approach failure, so the newer technology was acceptable for this application. Some electronics PoF applications have saved millions of dollars.

**2.2. Physics of Failure of Mechanical Systems.** AMSAA has applied the PoF process to mechanical systems as well. The work is involved with both the system and component levels. An example of system level work was the development of a complete dynamics model for a Ground Combat System (GCS). An example of component level analysis is the examination of a particular subsystem such as a vehicle suspension component through finite element or dynamics models. Both the system and component level analysis aid in the identification of root causes of failure. The PoF modeling and simulation combined with focused testing have provided more information, quicker and for less overall cost. PoF fatigue analysis is another important tool used to prevent failure. It involves collecting live data from the field or simulating a critical event through dynamics modeling. Finite element modeling is then used to convert loads or measured strains/accelerations to strain at critical locations. A statistical life prediction is

then developed using fatigue software and a variety of standards. Refer to Figure 1 for an outline of this process.

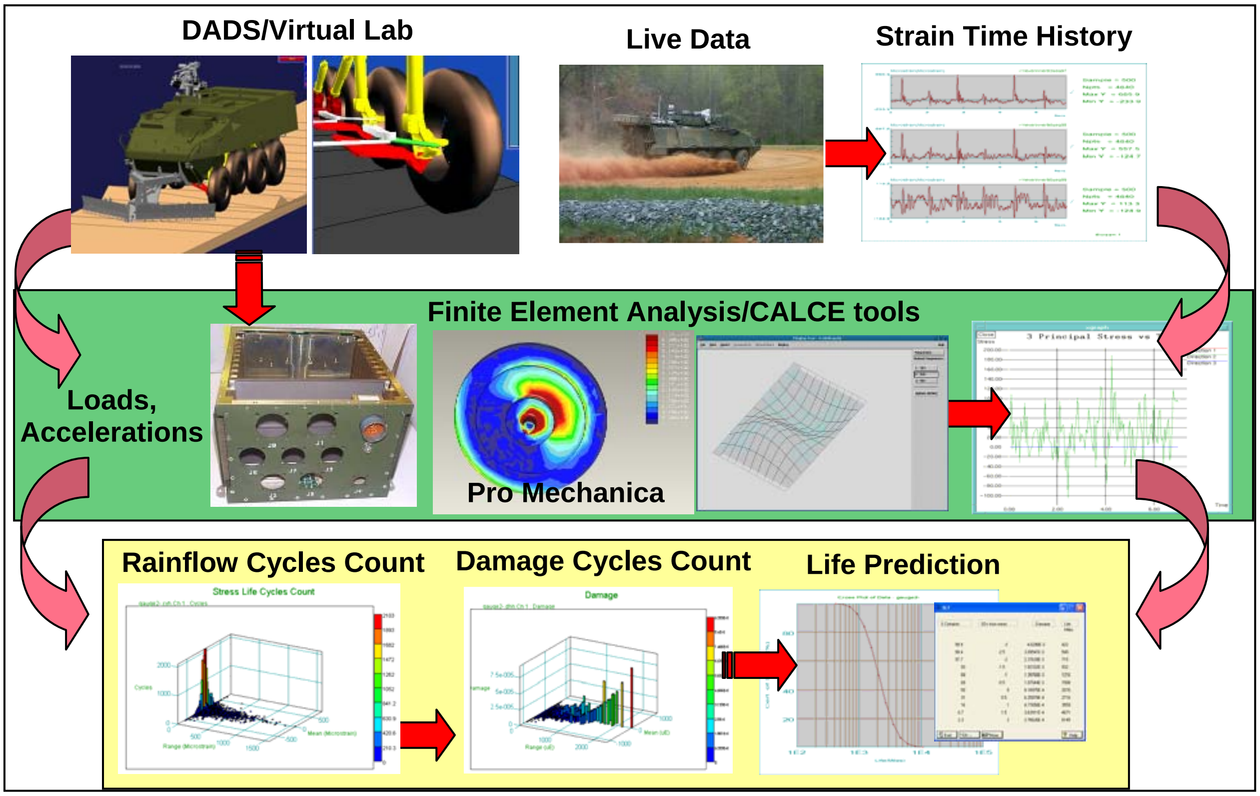


**Figure 1. Physics of Failure Fatigue Analysis Overview.**

An example where PoF was used to analyze a mechanical system failure was in the redesign of a hydraulic reservoir for a GCS. The hydraulic reservoir is a central depository for hydraulic oil from various components of a GCS including the primary steering system, rear ramp, cooling fan, upper deck fan, and front attachments. A failure of the reservoir would cause these systems to cease functioning until the reservoir has been replaced or repaired. A failure of the reservoir could also lead to a mission failure if those hydraulic systems were required. The purpose of the analysis was to compare the fatigue life of the original hydraulic reservoir to a redesigned reservoir. This was accomplished by extensive modeling, simulation and component level testing. AMSAA was tasked with using PoF to evaluate the redesign in order to avoid a costly and time consuming full-vehicle test. Failure mechanisms and locations from the field were documented. The most common were hairline cracks in the welds, but there were also pinhole leaks at corners, cracks on the exterior surface of an interior weld, and cracks along welds holding small attachments. AMSAA's PoF analysis consisted of two parts. The first was a dynamics model and simulation to predict loads and hot spots for the redesigned reservoir. This was used to conduct an analytical fatigue analysis to compare the design lives. The second part of the analysis was physical component testing to verify predicted improvement and add confidence in the redesign. The original reservoir was analyzed to build confidence in the model, and then the calculated failures were

compared to failures that occurred in the field.  While all failures did not correlate, many failure locations were predicted accurately.  The modeling and simulation was considered validated.  From this modeling and simulation it was shown that failure was unlikely for the redesigned reservoir.  The physical component testing verified results of the analysis.  It simulated 5200 miles of severe terrain.  The results of the test can be seen in Figure 2.

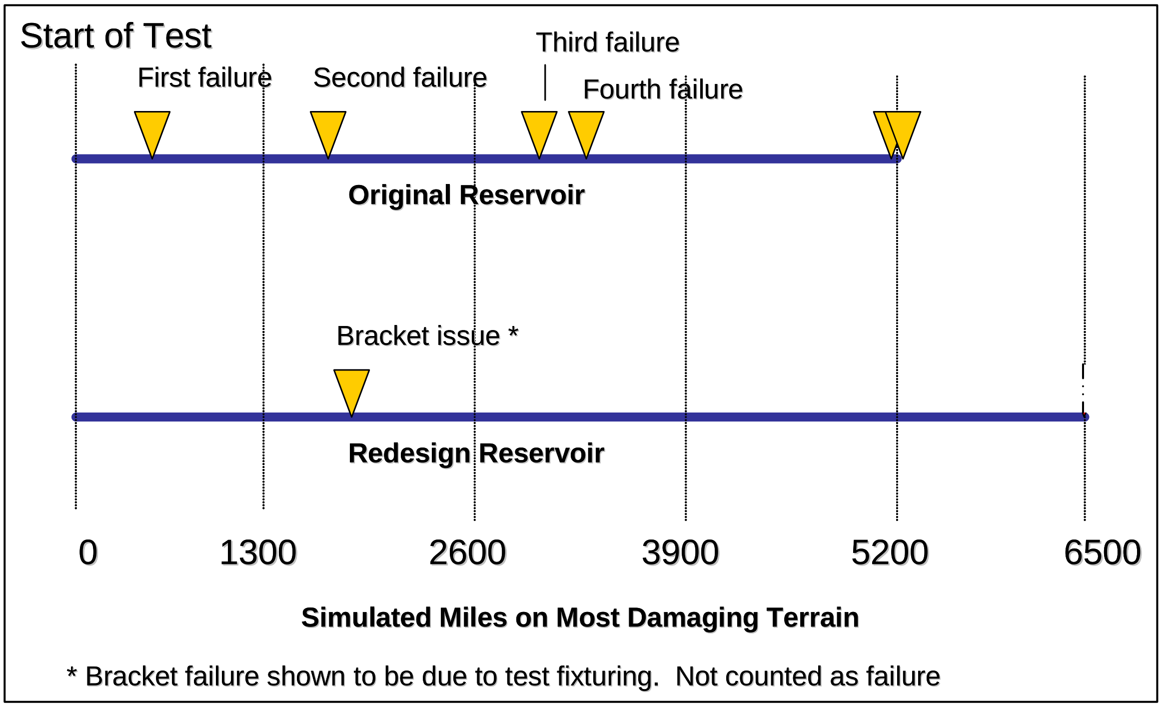


**Figure 2.  Physical Component Testing Results Summary.**

As you can see from Figure 2, the first failure on the original reservoir occurred within 1300 simulated miles of terrain while no official failures were found after 6500 simulated miles on the redesigned reservoir.  The failure on the bracket was determined to be caused by a preload in the test setup and would be highly unlikely to occur in the field.  Testing was halted after the redesigned reservoir demonstrated a significant increase in life over the original design.  It was concluded that the modeling and simulation were reasonably accurate in the prediction for fatigue life.  The redesigned reservoir is a suitable replacement for the original, in systems seeing high usage, due to the gain in fatigue life.  Use of the modeling and simulation allowed the reservoir to be evaluated in a cost and schedule effective manner when compared with a full vehicle test.

## 3. CONDITION BASED MAINTENANCE

Condition Based Maintenance (CBM) is a maintenance plan based not upon a schedule but rather the actual condition of a system and its components. This is enabled by application of usage, diagnostic, and prognostics processes executed on a Health and Usage Monitoring System (HUMS). Usage refers to how the system is employed and gives indications of how and why things are broken or breaking. Diagnostics is based on the symptoms or indicators of problems and uses methods to find what is broken and breaking in a system. Prognostics is based on a combination of indicators and/or PoF methods and uses methods for predicting when components are going to break.

AMSAA is focused on a vehicle self-diagnosing and self-reporting its own condition. Specifically, AMSAA is working on predictive maintenance algorithms using both the maintenance and operating histories of vehicles. The onboard system that AMSAA has designed in conjunction with the Aberdeen Test Center (ATC) at Aberdeen Proving Ground (APG), collects data from on board vehicle sensors, data bus, terrain sensors and a Global Positioning System (GPS), then analyzes the data in order to determine condition of the vehicle.

With the current capability of CBM, AMSAA has identified appropriate hardware and software for an Engineering Development HUMS (EDHUMS) and completed initial in-theater installations of data acquisition systems. AMSAA then developed a robust military-grade EDHUMS, designed a data analysis process, tested EDHUMS in the Continental United States training environment, and has fielded EDHUMS in operational units outside the Continental United States. AMSAA is currently working on developing an interim solution for the information management process using nCode's Library software.

AMSAA has successfully demonstrated hardware and software capabilities, data quality checks, and rudimentary usage characterization. Many vehicles have been fully instrumented and data is being captured from over 80 analog channels, multiple SAE J-1708 bus channels, and GPS sensors. These vehicles have run over all APG test courses multiple times which has provided detailed data for prognostic algorithm development. ATC and AMSAA have also measured and analyzed data from 20 wheeled vehicles of 3 different types in Iraq for over a year. This has provided some usage data although there have not yet been any on-board prognostic algorithms to identify impending failures, unsafe or damaging usage to the vehicle driver, maintainers, and commanders. The data is being aligned with maintenance records to evaluate the alignment of testing to actual usage.

EDHUMS testing has been ongoing since June 2006. AMSAA has instrumented Tactical Wheeled Vehicles at the National Training Center in Ft. Irwin, California. Data is currently being collected, reduced, analyzed and reported to fleet managers, engineers and maintainers. Usage characterization and initial versions of diagnostic/prognostic algorithms are installed and are being refined. Five EDHUMS systems were installed in Kuwait, December 2006, and five more systems were installed in Iraq, February 2007. In

addition, 6 systems were installed as part of the Heavy Brigade Combat Team demonstration which was scheduled for June 2007.

Some of the analyses that AMSAA has been able to provide include time in gear, fuel consumption, time at speed, and rudimentary terrain identification. AMSAA's goal is to generate this information using algorithms on-board which will help reduce the quantity of data that is processed off line.


**Figure 3. Latitude and Longitude Plot of Speed (green) and RMS Acceleration (pink) Values.**

Information can be provided as graphical displays, Figure 3 above, or a two-page vehicle usage summary report, Figure 4, which processes the data (using nCode GlyphWorks software) into a useful information report.

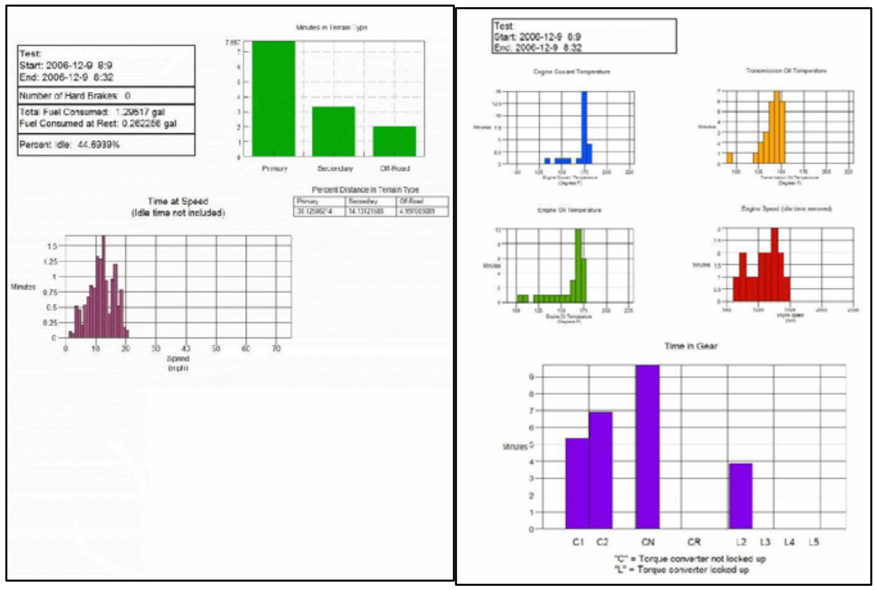


**Figure 4. Example of Two-Page Vehicle Usage Summary Report.**

AMSAA continues to meet with customers to further identify the type of information which is needed and how customers would like it displayed. The data flow processes from acquisition to reporting are being refined and AMSAA is phasing-in usage, diagnostic, prognostic algorithms for verification and validation as they are developed. CBM results have great potential to improve Army vehicle fleet management capabilities, improve reliability, and address specific component failures. AMSAA continues to work with Soldiers, industry and other government organizations to develop a robust CBM process which will result in significant logistics cost savings to the Army and improved materiel readiness.

## 4. CONCLUSIONS

Physics of Failure and Condition Based Maintenance provide more predictive rather than reactive capability. They significantly increase reliability and decrease operation and support costs of Army systems. Overall, they help achieve the top goal of providing better systems for the Warfighter.

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